Semiconductor and Integrated Optoelectronics (SIOE) Conference 2005

Optimisation of a two colour pumped Tm^{3+}-doped ZBLAN fibre amplifier at 1.49 μm

S. Tessarin, M. Lynch, J.F. Donegan and G. Mazé

Abstract: The authors have constructed a 4 metre length thulium-doped ZBLAN fibre amplifier optically pumped at 0.8 μm by a tuneable Ti : Sapphire and at 1.06 μm by an Nd^{3+} : YAG laser. The authors obtained 12.5 dB for small-signal gain at 60 mW for the two pumps' optical power. The behaviour of the amplifier has been analysed with the optical power of the signal approaching the saturation condition (−5 dBm) and at different wavelengths for the Ti : Sapphire pump laser. A model was developed for the optimisation of the amplifier for signal power below the saturation intensity at wavelengths between 1.49 and 1.53 μm (S-band). This shows an empirical quadratic dependence of the Nd^{3+} : YAG power with respect to the Ti : Sapphire power in order to obtain the maximum photon conversion efficiency making the optimised amplifier employable as a booster amplifier in the supporting telecommunication band.

1 Introduction

Much research into fibre amplifiers is focused on expanding the low-loss region of telecommunication transmission band wavelengths that are not yet covered by erbium and gain-shifted erbium fibre amplifiers. Thulium (Tm^{3+}) as dopant in glass has a fluorescence transition centred at 1.47 μm, which can be used as an amplifier at wavelengths between 1.43 and 1.53 μm (S^+-band extends from 1.43 to 1.49 μm and S-band extends from 1.49 to 1.53 μm) [1, 2].

In contrast to erbium amplifiers, thulium needs a low-phonon-energy host glass such as ZBLAN (ZnF_4–BF_2–LaF_2–AlF_2–NaF_2, a heavy metal fluoride glass) in which the 1.47 μm transition of the Tm^{3+} ions has higher radiative efficiency and the metastable level has a longer lifetime compared with silica.

However, as depicted in the energy level diagram (Fig. 1), the upper level for the transition $^3H_4$ has a lifetime of 1 ms, whereas the lower level $^3F_4$ has a lifetime of the order of 10 ms. This type of situation has been referred to as self-terminating transition and creates a 'bottleneck', where the population builds up in the terminating level, reducing the overall efficiency of the amplifier.

Higher efficiency can be achieved by upconverting the excess $^3F_4$ ion population to the $^3F_2$–$^3F_3$ thermally coupled levels through an excited state absorption (ESA) transition, which has an energy corresponding to wavelengths from 1.040 to 1.070 μm. A residual ground state absorption is also present at these wavelengths so single-wavelength pumping with Nd^{3+} : YAG (1.064 μm) or Yb^{3+} fibre lasers (1.047 μm) will generally produce some low-level of amplification [3]. However, because of the low pump absorption, long fluoride fibre lengths are necessary in order to obtain large gain.

The efficiency can be improved by directly pumping one of the ground state absorption transitions while the 1 μm radiation will be used essentially for upconverting the $^3F_4$ electrons population [4]. This type of configuration has been used to obtain the highest conversion efficiency observed to date for Tm^{3+}-doped fibre amplifiers with pumping at 1.56 μm (ground state) and 1.40 μm (excited state) [5].

The 800 nm technology for high power semiconductor lasers is well established because of the market for pump lasers for erbium fibre amplifiers [6] and for this reason, we have focused on this wavelength for pumping the strong thulium ground state absorption centred at 790 nm. In contrast, technology for high-power laser diodes at 1.05 μm is not fully developed and high powers are not readily obtainable.

There is clearly a need to investigate the performance of these dual pumped systems, particularly with regard to balancing the powers of the pump lasers for optimum amplifier performance. The aim of this paper is to present the experimental results that have been obtained for a thulium amplifier pumped at 1.06 μm and around 0.79 μm and use the measurements as a starting point for the construction of a model of the amplifier. This will allow us to optimise the ratio of the two pump powers involved.

2 Experimental set-up

A 4 metre length ZBLAN fluoride glass fibre with 2000 p.p.m. thulium doping level, 4.4-μm core diameter and NA = 0.17 was pumped simultaneously by a Ti : Sapphire tuneable laser in the range 760–820 nm and a YAG laser (1.064 μm). The pump lasers are combined using a Corning SMF-28 fibre chromatic coupler.

A single mode diode laser at 1.49 μm was used as a signal source to measure the amplifier gain. This is coupled counter-propagating to the pump lasers and detected with an optical spectrum analyser (OSA) as depicted in Fig. 2*a*.

The small-signal gain tuning curve along the amplifying wavelength region was measured by modifying the set-up

IEE Proceedings online no. 20050053

doi:10.1049/ip-opt:20050053

Paper first received 2nd June and in revised form 1st October 2005

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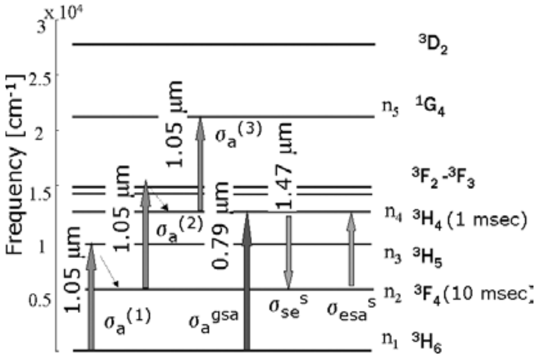

Fig. 1 *Diagram of the energy levels*

Upward arrows represent photons absorbed from the 1.064 μm pump, the ground state absorption at 790 nm and signal excited state absorption, whereas the downward arrow represents the signal stimulated emission at 1.49 μm. Each transition has an associated cross-section (4). The population densities for the levels involved in the model are named n_i with $i = 1$ to 5. Lifetimes of the amplifying levels are also given

presented in Fig. 2*b* using a broadband light source, a 75 W Xenon lamp coupled into a single mode fibre. This amplified signal from the fibre output was measured by using the OSA as a monochromator and passing its (electrical) signal output to a lock-in amplifier. Spectral resolution was set to 0.2 nm. The gain between 1.45 and 1.55 μm was recorded for different values of the 790 nm pump optical power.

3 Experimental results

With the optical power of both pumps at 60 mW and the Ti : Sapphire tuned to 790 nm, we have recorded from the OSA an amplification of 12.5 dB gain in the small-signal regime. In this case, the signal power was around −40 dBm and does not have an impact on the ion population of the levels involved in the amplification process.

The amplified Tm^{3+} fluorescence and the small-signal gain are shown in Fig. 3. The gain due to the 1.064-μm Nd^{3+} : YAG pump alone was 2 dB, whereas adding the 790 nm pump increased the gain to 12.5 dB. We also measured the behaviour of the amplifier at higher signal powers and at −5 dBm input signal power, the gain decreases to 0.7 dB below the small-signal case. For the model discussed in the next section, we chose an operating point of −10 dBm input signal level as representative of the onset of gain saturation.

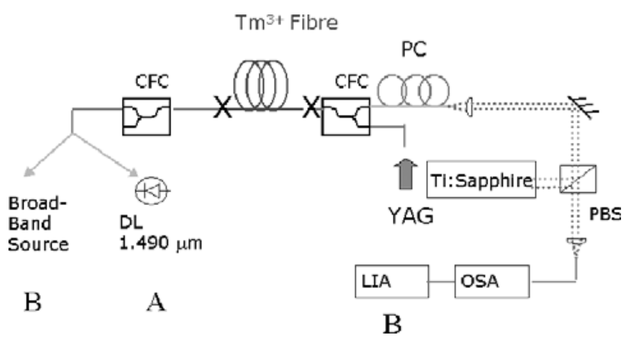

Fig. 2 *Schematic diagram showing the outline of the Tm amplifier*

The two pumps are coupled together by chromatic fibre coupler (CFC)

a The signal from a 1.49-μm single-mode laser diode is detected from the output of the amplifier after a polarising beam splitter (PBS). The polarisation controller (PC) maximises the signal throughput in the optical spectrum analyser (OSA)

b Light from a Xenon lamp is detected by reading the output of the OSA in a lock-in amplifier (LIA)

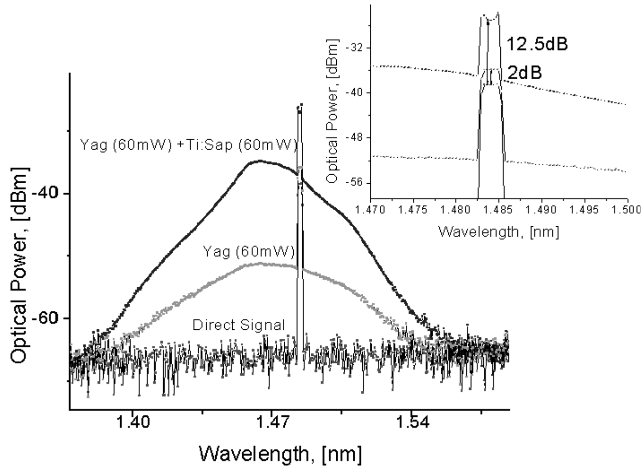

Fig. 3 *Detected Tm^{3+} fluorescence at 1.47 μm is reported when optical power for the two pumps is set to 60 mW and when only the 60 mW of 1.064 μm is present*

Inset shows the effect on the signal probe at 1.49 μm

The spectral response of the gain, measured with a broadband source, is shown in Fig. 4. The gain profile shows a significant redshift from the emission band which is centred at 1.47 μm and this is attributed to re-absorption.

Since changing the Ti : Sapphire wavelength will change the absorption cross-section, the pump at 790 nm can be tailored to access the value for the absorption cross-section where the maximum photon conversion efficiency (PCE) is obtained. This is defined as the ratio of the photon converted into signal and the number of injected pump photons

$$PCE = \frac{(P^s_{out} - P^s_{in})\lambda^s}{P^p_{TiS}\lambda^p_{TiS} + P^p_{YAG}\lambda^p_{YAG}} \tag{1}$$

where P^s is the signal input and output powers in the amplifier, λ^s the signal wavelength and P^p_{TiS}, λ^p_{TiS}, P^p_{YAG} and λ^p_{YAG} are the powers and wavelengths for the Ti : Sapphire and the Nd^{3+} : YAG pump lasers. As we have observed in Fig. 5 for 4 m length, the maximum PCE and gain achievable for 60 mW pump power of both Ti : Sapphire and Nd^{3+} : YAG is with the Ti : Sapphire tuned to 800 nm.

4 Optimisation

Optimisation criteria for fibre amplifiers will strongly depend on the intended application, for example preamplifiers require high gain with good gain linearity, whereas for high signal power (booster amplifier), output power and pumping efficiency are important considerations.

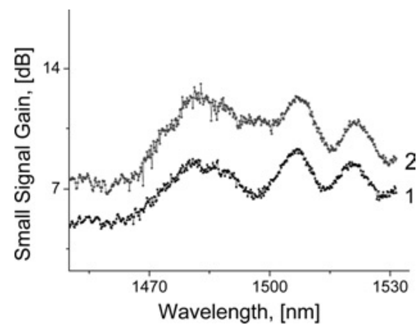

Fig. 4 *Gain for a different wavelength within the amplification band*

(1) Ti : Sapphire power of 30 mW, Nd^{3+} : YAG power 60 mW; (2) Ti : Sapphire power of 60 mW, Nd^{3+} : YAG power 60 mW

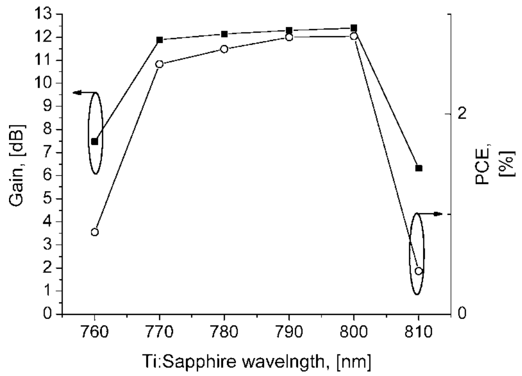

Fig. 5 *Measured gain and PCE observed for different Ti : Sapphire pump wavelengths*

Here, we concentrate on the intermediate case with −10 dBm input signal level as representative of the onset of gain saturation. The optimisation criterion we have chosen is to maximise the pump to signal conversion efficiency. This is important for a booster amplifier as the performance of a practical amplifier is often limited by the pump powers available from laser diodes. At these signal levels, the effect of the amplified spontaneous emission is not significant and is not considered here.

For the dual-wavelength pumped Tm^{3+} system, the terminating level is depleted by the secondary pump so we can expect it to have good saturation characteristics once the photon conversion efficiency is high. An estimate of the saturation intensity in the limit of total bleaching of the terminating level is given by [7]

$$I^s_{Sat} = \frac{h\nu^s}{\sigma^s_{se}\tau'_4} \tag{2}$$

so for a cross-section of the order of 2.5×10^{-25} m^2 and a lifetime of the $^3H_4$ level (number 4, in Fig. 1) of 1 ms gives a saturation intensity of 5×10^{11} mW/m^2 or, in the case of our fibre, gives a saturating signal power of +9 dBm.

This makes the Tm^{3+} two-colour pumped fibre particularly suitable for a gain-shifted booster amplifier since it can operate at a high-level of signal input and low pump powers at wavelengths between 1.49 and 1.53 μm (S-band).

As experimentally observed, we selected the starting point for our analysis at the input signal power of −10 dBm, the Ti : Sapphire tuned at 800 nm and the fibre with the same doping and parameters (NA, core diameter, length) as the one tested.

Since operation at 1.47 μm is reduced by lower relative inversion and/or re-absorption, we limit our analysis to the 1.49-μm operation where these effects can be neglected. The model that has been developed is similar to that published by Kasamatsu *et al.* [8] where the steady-state population of the relevant levels has been numerically integrated simultaneously with the propagation equations using a fourth-order Runge-Kutta method.

Thulium in ZBLAN at 1.47 μm is a four-level system and therefore high conversion efficiency is expected. A threshold power is due to the self-terminating nature of the 1.49 μm transition; however, in the presence of an efficient upconversion for the $^3H_4$ population, the gain coefficient at 1.49 μm $\gamma^s = \sigma^s_{se}n_4 - \sigma^s_{esa}n_2$ is positive due to the small σ^s_{esa} [9] and the optimum fibre length is set in order to absorb as much pump power as possible [10]. The σ^s_{se} is the signal stimulated emission cross-section whereas σ^s_{esa} is the signal ESA cross-section and n_4 and n_2 are the population densities of the two levels involved in the process of signal amplification as depicted in Fig. 1.

The signal propagation is governed by a differential equation where P^s is the signal power at the z point in the fibre

$$\frac{dP^s}{dz} = -\gamma^s P^s \tag{3}$$

the minus sign is due to the counter propagation of pumps and signals and the γ^s is the gain coefficient.

Equation (3) has to be integrated simultaneously with the pump propagation equations and can be written as

$$\begin{aligned} \frac{dP^{TiS}}{dz} &= -\Gamma(\lambda^{TiS})\gamma^{TiS}P^{TiS} - \alpha_{800} \\ \frac{dP^{YAG}}{dz} &= -\Gamma(\lambda^{YAG})\gamma^{YAG}P^{YAG} - \alpha_{1064} \end{aligned} \tag{4}$$

where $\Gamma(\lambda^{TiS})$ and $\Gamma(\lambda^{YAG})$ are coefficients which take into account the multimode nature of the two pumps and α_{800} and α_{1064} are backscattering losses of the ZBLAN fibre at the two pumps wavelength. We used the approximation $\alpha_{800} \simeq \alpha_{1064} \simeq 0.1$ dB/m as reported in the specification of the ZBLAN fibre.

The γ^{TiS} and γ^{YAG} terms in (4) are the absorption coefficients for the two pumps given by

$$\begin{aligned} \gamma^{TiS} &= -\sigma^{gsa}_a(\lambda^{TiS})n_1 \\ \gamma^{YAG} &= -\sigma^{(1)}_a(\lambda^{YAG})n_1 - \sigma^{(2)}_a(\lambda^{YAG})n_2 - \sigma^{(3)}_a(\lambda^{YAG})n_4 \end{aligned} \tag{5}$$

where the various absorption cross-sections involved and the population densities of the electronic levels (n_i) are shown in Fig. 1 and listed in Table 1.

All the population densities are described by rate equations and the steady-state value is obtained by algebraically solving the rate equations together with the conservation equation.

The structure of the amplifier was taken into account by the two boundary conditions to which (4) and (5) are subjected and represent the fact that the two pumps are injected in the fibre at $z = 0$ while the signal is counter-propagating from the other end of the active fibre.

The Tm^{3+}-doped ZBLAN fibre has been designed in order to obtain high transmission with Corning SMF-28 fibre with Marcuse's polynomial spot size [11] of the active fibre matching with the fundamental LP_{01} mode of the transmission fibre above the cut-off wavelength. The Kasamatsu overlapping factor $\Gamma(\lambda)$ in (4) describes the overlap of the pump mode with the fibre core dopant. This has been obtained by measuring the transmission of the fibre at the Ti : Sapphire wavelength. This gives $\Gamma(\lambda_{TiS}) = 0.52$. The $\Gamma(\lambda_{YAG})$ was estimated to be equal to 0.94 from the ratio of the radius of the fibre and the Gaussian spot size calculated from the polynomial expression reported in [12].

All the parameters used in the simulation are reported in Table 1.

Fig. 6 shows the calculated gain and the PCE as a function of the two pump powers. The gain measured for 30 mW of Ti : Sapphire and 60 mW of Nd^{3+} : YAG as shown in Fig. 4 is 7.2 dB and the calculated value is 7.04 dB, whereas with 60 mW of Ti : Sapphire the measured gain is 12.5 dB and the calculated gain is 13.2 dB, showing good agreement. For a given Ti : Sapphire power, a fast increase in gain with Nd^{3+} : YAG power is seen, because of the depletion of the terminating level, after which the gain is almost independent of the Nd^{3+} : YAG power due to the small GSA absorption at 1.064 μm. The transition

Table 1: Parameters that have been used in the numerical simulation

Parameter	Unit	Symbol	Value	Remarks
Thulium concentration	m^{-3}		3.2×10^{25}	Specification
Core diameter	μm		4.4	Specification
NA			0.17	Specification
Background loss	dB/m		0.1	Specification
Signal stimulated emission cross-section	m^2	σ_{se}^{s}	1.5×10^{-25}	[14]
Signal ESA cross-section	m^2	σ_{esa}^{s}	0.9×10^{-27}	[14]
Absorption cross-section 800 nm	m^2	σ_{a}^{gsa}	1.9×10^{-25}	[14]
Absorption cross-section 1.064 μm	m^2	$\sigma_{a}^{(1)}$	1.1×10^{-27}	[15]
	m^2	$\sigma_{a}^{(2)}$	8.2×10^{-25}	[15]
	m^2	$\sigma_{a}^{(3)}$	2.5×10^{-27}	[15]
Overlapping factor 800 nm		$\Gamma(\lambda_{TiS})$	0.52	Measured
Overlapping factor 1.064 μm		$\Gamma(\lambda_{YAG})$	0.94	Estimated [12]
Spontaneous emission rate	s^{-1}			Used for the rate equations [8, 14]

between these two regimes can be seen as a maximum in the PCE. At a given Ti : Sapphire power, the PCE will sharply rise with the increase of the Nd^{3+} : YAG power and then as the terminating level is bleached, the PCE will decrease. The contour of maximum PCE gives the optimum pump power combination and can be approximated by a quadratic equation given the best ratio between Ti : Sapphire power and Nd^{3+} : YAG power as

$$P_{YAG} = 3.2 P^2_{Ti:Sapphire} \qquad (6)$$

We have defined the PCE as the number of stimulated emitted photons normalised by the total number of pump photons (eq. 6.2); considering only the two strongest absorption mechanisms the theoretical limit will be 50%. However, a more reasonable figure observed in a real amplifier [13] is around 30% which is close to the limit reached by PCE for Ti : Sapphire power above 150 mW and Nd^{3+} : YAG power above 75 mW. Longer fibre length is not needed since high PCE performance can be achieved in the short fibre. The longer fibre will reduce the obtainable limit because of the scattering loss associated with the two pumps and the signal.

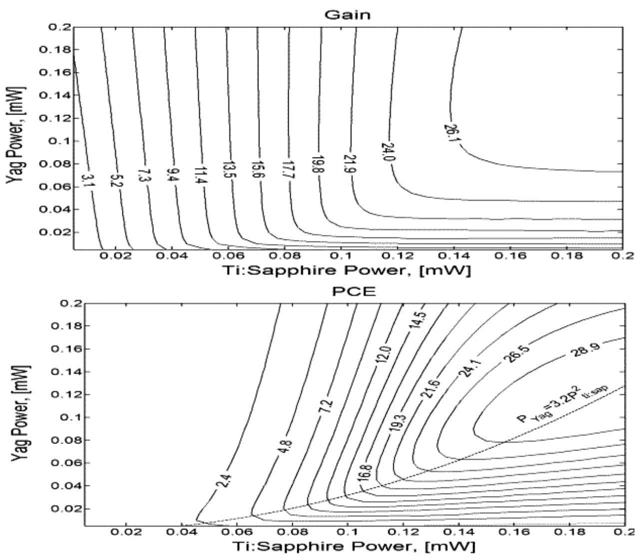

Fig. 6 *Calculated gain and PCE for different values of the two pump powers*
Maximum value for the PCE with respect to the pumps is shown as a dashed line

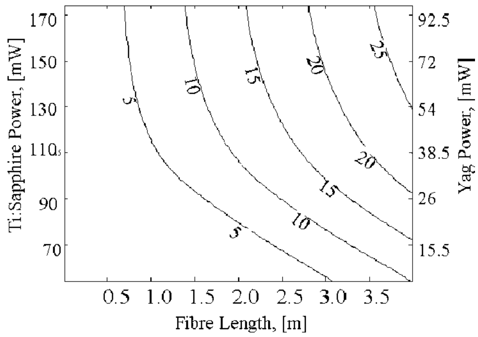

Fig. 7 *Gain predicted within the fibre for the two pumps when the power for the Nd^{3+}:YAG is correlated to the Ti:Sapphire by the relationship (6)*

In Fig. 7, we report the expected gain within the fibre length for the two pump powers. Starting from the left-hand side of Fig. 7, it is possible to calculate the 800 nm power required in order to obtain the maximum PCE and the gain obtained as a function of the length of the active fibre. The method can be used for different pumping schemes and can be tailored in order to fulfil different types of conditions and fibre geometry.

5 Conclusions

We have constructed a 4 m length thulium-doped ZBLAN fibre amplifier pumped by a Nd^{3+} : YAG (1.064 μm) laser and a Ti : Sapphire (800 nm) laser with the intention of optimising the operation of the amplifier for high-signal gain at a wavelength above 1.49 μm. Experimental observations suggest the best pump wavelength is located at 800 nm for the Ti : Sapphire and practical signal operation of −10 dBm does not considerably affect the gain at 1.49 μm.

High-signal operation requires maximum photon conversion efficiency and we have developed a model, not limited to the small-signal gain, in order to find the operation points where the maximum PCE is obtained for the lowest optical power of the two pumps involved.

For a given value of the Ti : Sapphire power, we established that the corresponding value for the Nd^{3+} : YAG power obeys a quadratic relationship.

We profiled the gain within the fibre length of the amplifier so that the required length in order to achieve the desired gain can be found.

6 Acknowledgment

The Tm^{3+} ZBLAN doped fibre used in this work was provided by Le Verre Fluore', Brittany.

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